COVER SHEET

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REENGINEERING HIGH-RISE CONSTRUCTION FOR ENHANCED CYCLE TIME AND SAFETY

S. L. Kajewski
Queensland University of Technology, Brisbane, Australia
K. Hampson
Queensland University of Technology, Brisbane, Australia

Abstract
Construction of high-rise concrete buildings relies extensively on multi-level formworking; a process in which a limited number of formwork and shoring sets are cycled up the structure as construction progresses. This multi-level formworking procedure relies on supporting a freshly cast slab on a number of lower level slabs, which may or may not have attained their full strength. Currently, the multi-level formwork shoring procedure and slab construction cycle times for buildings with post-tensioned slabs are selected based on the requirements for conventionally reinforced slabs. As such, cycle times of 4 or 5 days and 3 or 4 levels of shoring are common. This paper proposes, however, that due to the inherently different behavior of post-tensioned slabs, it may be possible to shorten slab cycle times, reduce formwork and shoring materials and improve construction safety.

Keywords: Multi-level formwork; post-tensioning; reshoring; shoring.

Stephen L. Kajewski is a Lecturer in the School of Construction Management and Property at QUT. His research interests include multi-level formworking processes, prestressed concrete, international construction practices and high-rise construction techniques and methodologies.

Keith Hampson is Director of Research and a Senior Lecturer in the School of Construction Management and Property at QUT. He teaches and researches strategic technology management and advanced construction methods within the context of business performance.

INTRODUCTION

When designing high rise structures, designers spend considerable time, effort and cost on the analysis and documentation of the permanent structure. Unfortunately, this attention does not always extend to the permanent structure during construction or to the temporary structure supporting the structure being constructed. All to often, the method of multi-level formworking adopted on a project is selected based on local practice or the last successful project.

When examining the requirements for multi-level formwork for post-tensioned slabs, designers often select and analyse the formworking system on the simplifying assumption that it is conservative to treat the slab as if it were conventionally reinforced. Post-tensioned slabs, however, behave inherently differently to conventionally reinforced slabs with the post-tensioning causing a redistribution of the loads upwards. This reduces the loads on the lower level slabs and increases the loads on the upper level slabs; a phenomenon not occurring with conventionally reinforced slabs. The load distribution that occurs between interconnected post-tensioned slabs when multi-level formworking should therefore be significantly different to that of a conventionally reinforced slab system. If the formwork shores are partially or fully unloaded by the effects of the post-tensioning, it may be possible to shorten slab cycle times, reduce formwork and shoring materials and improve construction safety.

FORMING MULTI-LEVEL STRUCTURES

In an ideal formworking situation for a multi-level structure, the formwork shores required to support the formwork and freshly placed concrete would continue to the foundation or ground level of the structure. In this scenario, the slabs are not required to carry their own weight, the weight of slabs above or other applied construction loads. Instead, all such loads are carried from the point of application, via the shores, to the ground.

Whilst maintaining a continuous load path to the foundations is certainly possible, and even common for low-rise structures, it is neither a practical, nor a cost effective solution for the forming of most multi-level structures. Formworking for multi-level structures relies on a limited number of lower level slabs supporting the freshly placed slabs. In essence, this means that freshly poured slabs are often supported on lower level slabs that have yet to attain their full strength.

There are three common multi-level shoring options: undisturbed supports, backpropping and reshoring. With a system of undisturbed supports, the shores supporting the formwork remain undisturbed in their original position for the entire period over which the slab is required to be supported. As the slab remains fully supported whilst the shores are undisturbed, the slab is not required to carry any of its own load. The load from the freshly cast slab is fully transferred to the foundation level provided a continuous load path is available. If however load path to the foundation has been broken, the lower slab levels, interconnected by shoring, support the new slab load in proportion to their relative stiffness.

When adopting a backpropping (backshoring) procedure, there are two common variations. The more rigorous process involves the installation of a secondary shore, adjacent to the original shores, directly supporting the formwork. When in position, the original shore and formwork up to this secondary shore is removed and the weight of the slab is transferred to the secondary shore. A third shore is then installed snugly under the exposed slab soffit, in the approximately the same position as the original shore. The secondary shore and remaining formwork is then able to be removed. A less rigorous but more practical process of backpropping involves stripping small areas of the slab, without the use of secondary shores and then backpropping the exposed area of the slab. This alternative allows the slab to deflect slightly but does not result in a significant redistribution of loads.

The process of reshoring is similar to backpropping in that some portion of the slab is stripped prior to the installation of the reshores. With reshoring, however, larger areas of slab, often entire structural bays, are stripped prior to the installation of the shores. With the entire bay of the slab soffit exposed and unsupported, the slab is able to fully deflect. This forces the slab to support its self-weight and some portion of the slab and construction loads over as a new load sharing equilibrium is reached amongst the interconnected slabs. Reshoring results in a load redistribution up through the structure of interconnected slabs, requiring the younger slabs to accept loads of greater magnitude earlier than that required with backpropping. Provided the shoring remains in contact with the foundations, the shoring loads are cumulative with a maximum shore load occurring at the lowest level (Nielsen 1952, Grundy and Kabaila 1963). With reshoring, the only loads in the shores are due to the weight of the freshly cast slab and any applied construction loads.

MULTI-LEVEL FORMWORK AND POST-TENSIONED CONCRETE

The standards and codes of practice dealing with multi-level formworking for conventionally reinforced concrete slabs provide minimal guidance for the designer. The guidance provided to the designer for post-tensioned slabs is even less. Of the two Australian Standards dealing with the concrete construction (AS3600 Concrete Structures 1988, AS3610 Formwork for Concrete 1990), AS3600 (1988, clause 19.6.2.7) contains the only reference to formwork for stressed slabs and states:

> *Formwork shall not be stripped and formwork supports shall not be removed from the soffits of prestressed concrete slabs or beams until the strength of the concrete in the member and the number of tendons stressed are such as to provide the necessary strength to carry the dead and construction loads.*

ACI Committee 347 (1988) and Hurd (1989) provide more guidance but the simple principles and precautions outlined refer to the redistribution of the slab load on the floor being stressed only. They do not examine any vertical redistribution between the interconnected slabs. The examination by ACI Committee 347 (1988) and Hurd (1989) assumes that prior to stressing, each shore carries a share of the slab dead weight (and any other construction loads) in proportion to the area of slab supported. During stressing, as the slab lifts and some of this applied load is balanced, a redistribution of load occurs from the inner shores within the slab span to the outer shores along the line of support. This results in a reduction or possible elimination of the loads on the internal shores (depending on the level of stressing). This also results in an increase of the loads on the outer (line of support) shores, possibly resulting in an overload situation.

ACI Committee 347 (1988, clause 3.8.7) best advises the designer of the actions during post-tensioning of slabs:

> *The design and placement of shores, reshores, and backshores for post-tensioned construction requires more consideration than for normal reinforced concrete. The stressing of post-tensioning steel can cause overloads to occur in shores, reshores, or backshores or other temporary supports. The stressing sequence appears to have the greatest effect. When a slab is post-tensioned, the force in the tendon produces downward load at the beam. If the beam is shored, the shoring must carry this added load. Magnitude of the load may approach the dead weight of the*

contributory area of the slab. If the floor slab is tensioned before the supporting beams and girders, a careful analysis of the load transfer to the beam or girder shores, reshores, or backshores will be required.

Whilst the above are certainly important considerations when designing formwork for post-tensioned concrete structures, no guidance is given as to the effect that the stressing process may have on multi-level formworking.

Post-tensioning and slab lift

When shoring is removed, all suspended concrete slabs deflect elastically under the effects of self-weight and any applied loads. If the slab is conventionally reinforced, this deflection is irreversible. If a slab is post-tensioned with tendons that are draped parabolically, some portion of the deflection is able to be reversed through a process of load-balancing. This reversal is possible as the draped tendons produce an uplift force as they are tensioned as indicated in Figure 1.

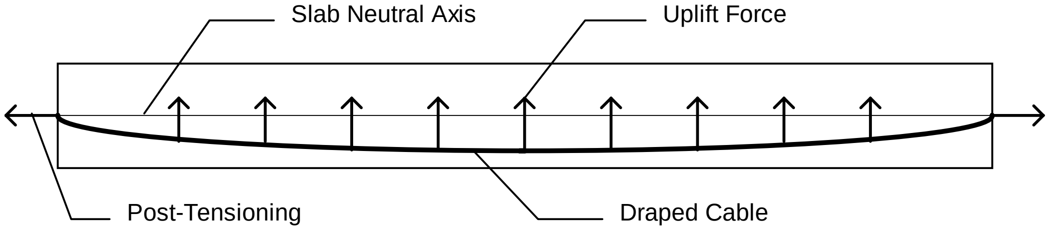
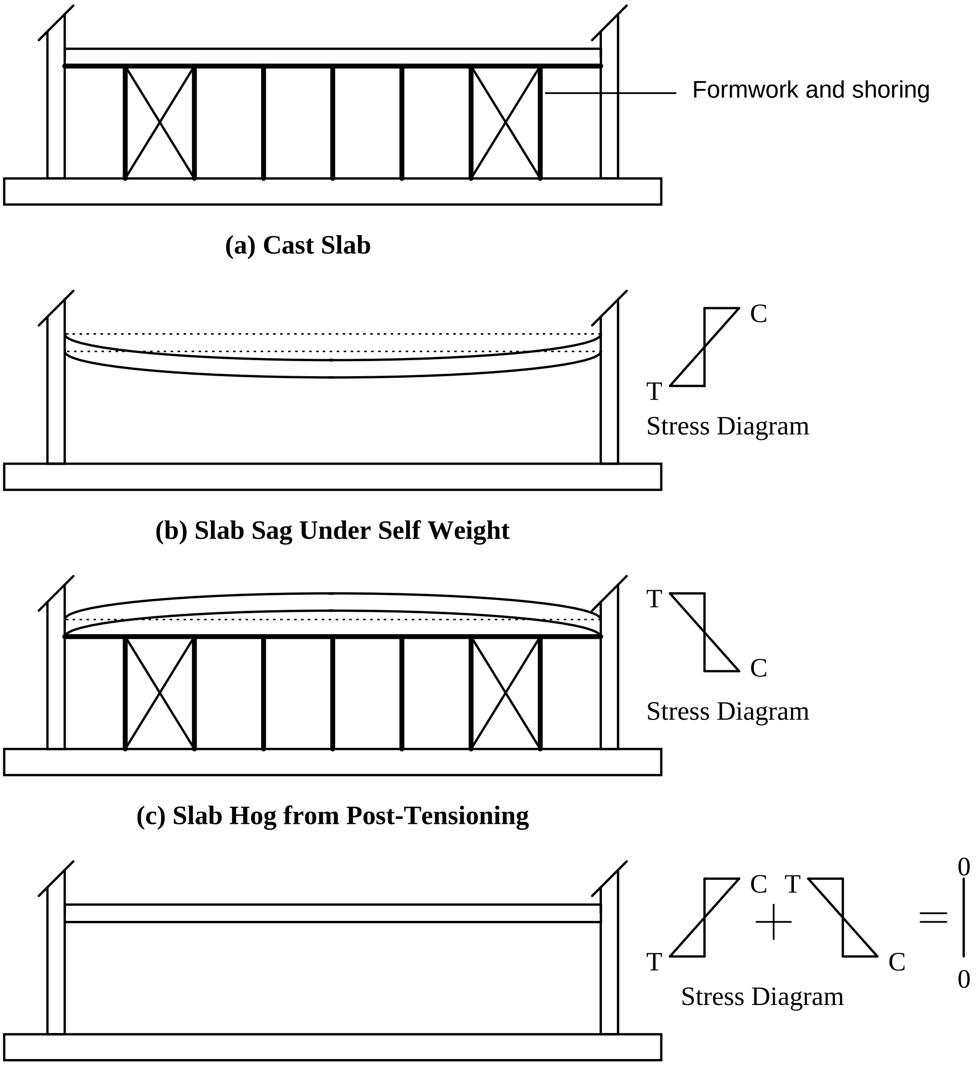


Figure 1. Uplift force from draped post-tensioning tendons

The process of load-balancing is indicated in Figure 2. As shown in Figure 2(a), a slab when first cast, is fully supported by the formwork and shoring. As such, it is unable to deflect resulting in a level slab that is not subjected to any bending stresses. If the formwork and shoring were removed prior to post-tensioning, the slab would deflect under its self-weight resulting in a slab sag situation with tensile stresses in the lower portion of the slab and compressive stresses in the upper portion of the slab as indicated in Figure 2(b). If the slab was post-tensioned prior to the removal of the formwork, a slab hog situation would result with tensile stresses in the upper portion of the slab and compressive stresses in the lower portion of the slab as indicated in Figure 2(c). If a level of post-tensioning is adopted such that it produces internal stresses equal but opposite to the self-weight stresses, a level slab results as indicated in Figure 2(d). In this situation, it is can be said that 100% of the slab self-weight has been balanced (full load-balancing). It should be noted that engineers do not always design for full load-balancing; a lesser or greater load may be balanced depending on the desired effect.

Post-tensioning and the effect on shore loads

If the assumption of slab lift under the effects of post-tensioning is held to be true and if the post-tensioning is applied before the formwork and shoring is removed (the usual practice), the shoring is unloaded by an amount equal to the portion of the slab self-weight that is balanced. As the slab is poured, the formwork deflects and the shoring shortens under the load from the concrete self-weight. As the concrete does not have any flexural strength at this stage, the shores are required to carry the full slab load. If full load-balancing is adopted, the slab will lift to a level state forcing the slab to support its own self-weight thereby completely unloading the shores. If less than the full self-weight is balanced, the slab will lift partially forcing it to support that portion of the load that was balanced with the unbalanced portion of the load remaining in the shores. This phenomenon was first proposed by Kajewski et al. (1995,1996).



(a) Cast Slab

(b) Slab Sag Under Self Weight

(c) Slab Hog from Post-Tensioning

(d) Load-Balanced Situation

Figure 2. Load balancing

PREDICTING SLAB AND SHORING LOADS

The Grundy and Kabaila (1963) simplified method is used in this report to predict the slab and shore loads that occur when multi-level formworking. This simplified method is not described in detail here. Simply, the procedure expresses the loads in the slabs and shores in multiples of typical slab loads (expressed as a slab load ratio) and assumes that the loads are distributed between the interconnected slabs in direct proportion to their relative stiffness. For example, a slab load ratio of 1.20 in a shore indicates that the shore is carrying the equivalent of 1.20 times the typical slab load for the slab area supported by the shore. It should be noted at the outset that the method developed by Grundy and Kabaila (1963) has a number of simplifying assumptions that limit the accuracy of the results obtained. As it is the intention of this paper to demonstrate some possibilities with multi-level post-tensioned work, the method of Grundy and Kabaila will be sufficient to allow comparisons to be drawn between conventionally reinforced slabs and post-tensioned slabs.

EXAMINATION OF SHORING SCENARIOS

To demonstrate some possibilities for shoring procedures with post-tensioned flat plate slabs, four scenarios are examined:

1. conventionally reinforced - undisturbed support system (backpropping similar);
2. post-tensioned - undisturbed support system (backpropping similar);
3. conventionally reinforced - reshored system;
4. post-tensioned - reshored system.

To model the effects of the post-tensioning, the full slab dead load is assumed to be balanced. That is, at the level of full stress the slab carries its full self-weight, thereby, not contributing to the supporting shore or reshore loads. It is also assumed that the slabs are poured on a 7 day cycle and are stripped at an age of 20 days. It should be noted that the shoring procedure procedures and cycle times adopted do not necessarily conform to the requirements of the relevant Australian Standards; they are provided for comparison purposes only. The concrete elasticity and compressive strength assumed in the scenarios are indicated in Figure 3.

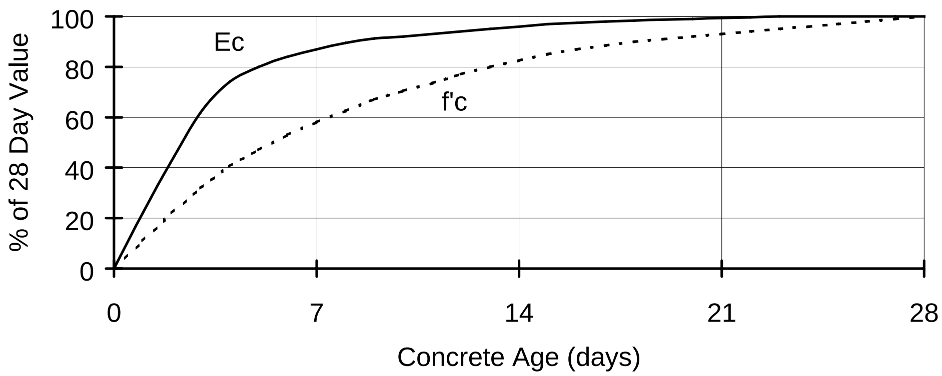


Figure 3. Assumed concrete properties

Scenario 1: conventionally reinforced - undisturbed support system (backpropping similar)

Reproduced from the classic example of Grundy and Kabaila (1953), Figure 4 indicates a maximum slab ratio of 2.37 occurring on the level 3 slab at day 42. This slab has an age of 21 days. The level 3 slab was the last slab poured prior to the removal of the foundation level shores. Regardless of the number of shored levels, the last slab poured prior to the removal of the foundation level shores will always be subjected to the largest slab load ratio.

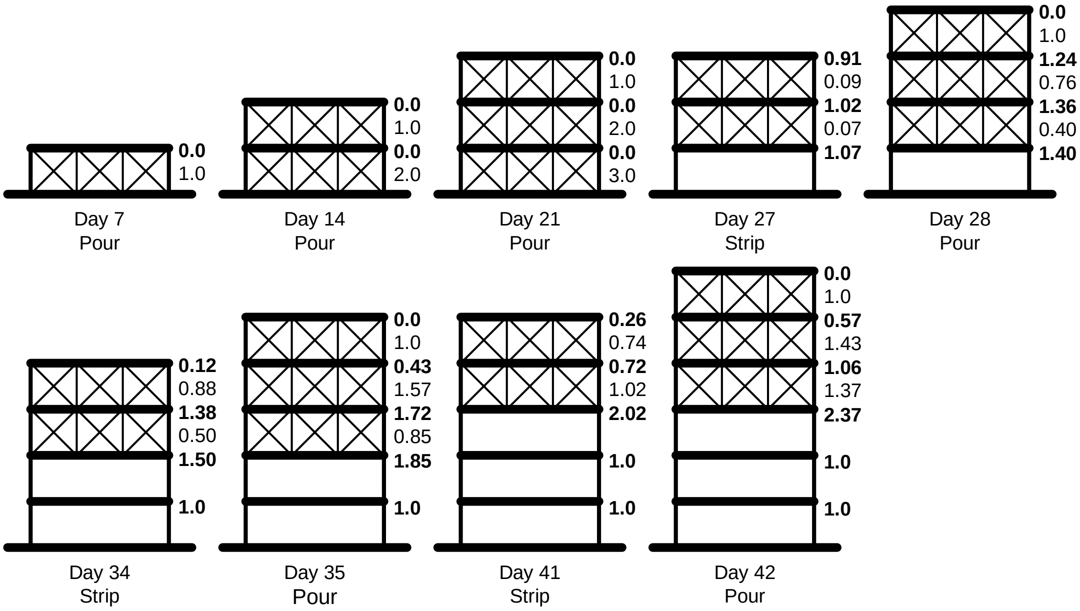


Figure 4. Slab load ratios (undisturbed supports - conventionally reinforced)

Scenario 2: post-tensioned - undisturbed support system (backpropping similar)
Subject to the load balancing assumption outlined previously, when stressing a slab, the shores supporting the slab are assumed to be relieved of the slab load. This is most clearly indicated at day 12 in Figure 5. As indicated, the maximum slab load ratio in the post-tensioned system is reduced to 1.35. The age of the slab is also 21 days. This maximum ratio no longer occurs in the last slab poured prior to the removal of the foundation level shores but now occurs at the lowest slab of the interconnected system. The slab load ratios indicated at day 28 repeat up the structure at each pour date with the lowest level slab in the interconnected system being subjected to a load ratio of 1.35 at each pour date.

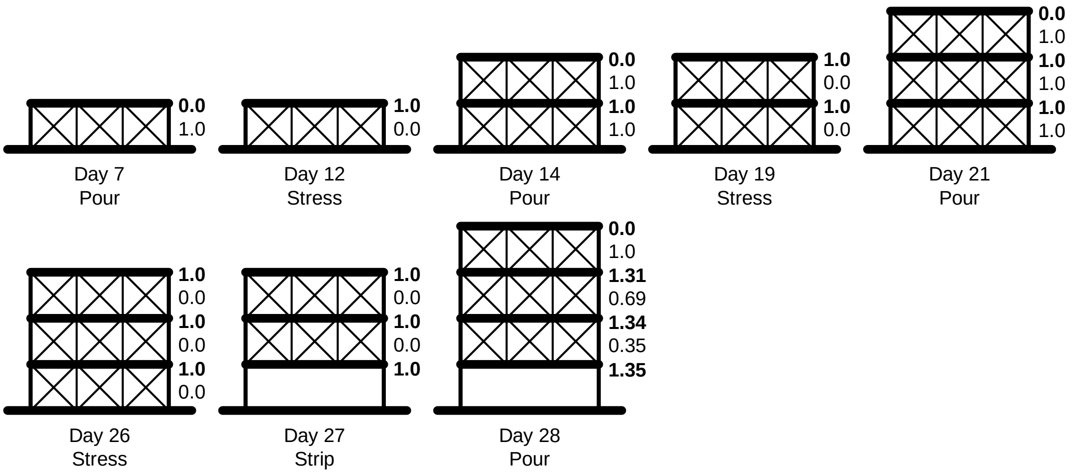


Figure 5. Slab load ratios (undisturbed supports - post-tensioned)

Scenario 3: conventionally reinforced - reshored system

The perceived benefits of reshoring a conventionally reinforced slab is highlighted in Figure 6. Reshoring, by allowing slabs to carry loads earlier, reduces the maximum load ratio from 2.37 to 1.85. This reduction is not as significant as it first appears as the age of the slab at which this maximum occurs is 14 days rather than 21 days as was the case in the undisturbed system (Figure 4).

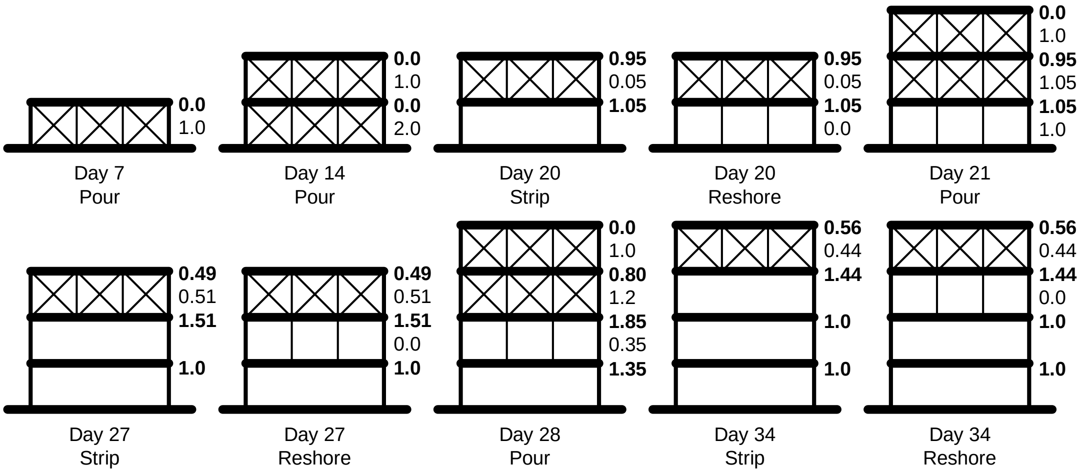


Figure 6. Slab load ratios (reshored - conventionally reinforced)

Scenario 4: post-tensioned - reshored system

The reshored post-tensioned system in Figure 7 indicates a maximum slab load ratio of 1.35. The slab load ratios produced in this system are identical to the undisturbed system.

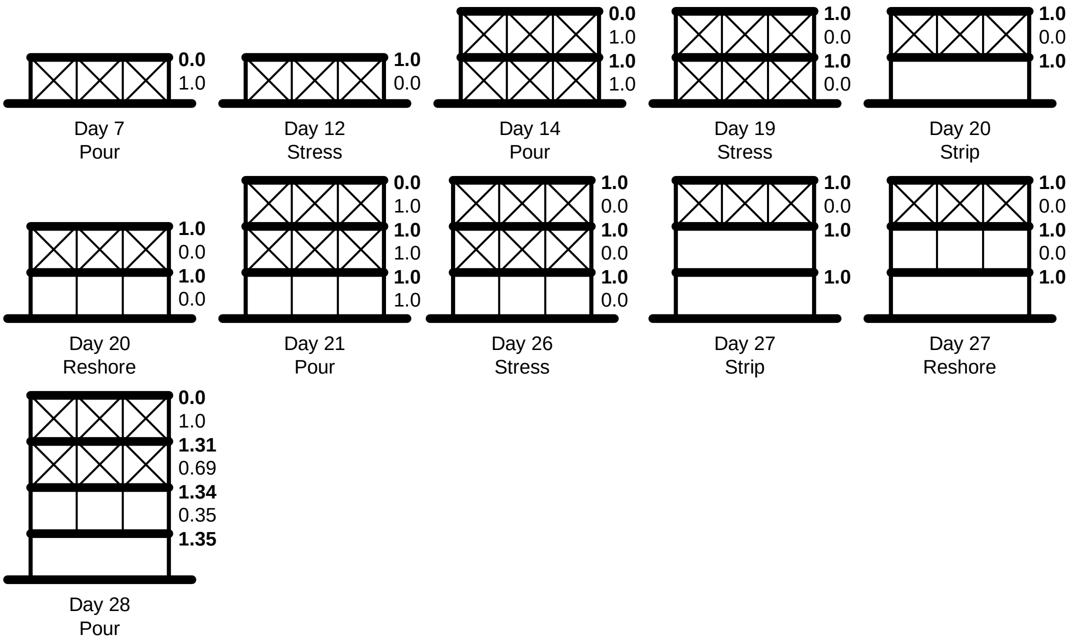


Figure 7 Slab load ratios (reshored - post-tensioned)

IMPROVEMENTS TO CONSTRUCTION PRACTICE

Improvements to construction safety

Comparison of the maximum slab load ratios is insufficient as a means of direct comparison. It is necessary to account for the relative age and flexural strength of the slab in question. Hurd and Courtois (1984) detail a method of determining factors of safety based on the assumption that the strength of a slab at a given age is proportional to the percentage of the 28 day (ultimate) strength. This method is adopted for this paper.

Assuming a slab thickness of 150 mm, the slab dead load (G) is 3.53 kPa. The design live load (Q) assumed is 3 kPa which is equivalent to 0.85G. Concrete structures in Australia are designed according to AS3600 (1988, clause 3.3) for an ultimate load of:

$$F_u = 1.25G + 1.5Q \qquad (1)$$

where:

F_u = ultimate design load

G=dead load

Q = live load

For the loads assumed, the 28 day ultimate capacity of a slab is therefore:

$$W_u = 1.25G + 1.5(0.85G) = 2.53G$$

AS3610 (1990, clause 4.4) indicates that during construction, the live loads to be assumed for a multi-level formwork system are 1 kPa on the uppermost slab and 0.25 kPa on all lower level supporting slabs. As such, with 3 levels of supporting slabs and 1 freshly cast slab, the average live load during construction is 0.44 kPa or 0.12G. With 2 supporting levels and 1 freshly cast slab, the average live load during construction is 0.5 kPa or 0.14G. The actual load on a slab is the slab load ratio multiplied by the sum of the dead load plus average construction live load.

For example, consider the slab load ratio of 1.07 for the 20 day old slab indicated at day 27 in Figure 4. From Figure 3, at an age of 20 days, the concrete has 92% of its ultimate strength. Thus the factor of safety for this particular slab would be:

$$F.O.S = \frac{0.92x2.53G}{\left(1G + 0.14G\right)x1.07} = 1.91$$

Table 1 indicates the lowest factor of safety for each of the four scenarios. When comparing the undisturbed support systems, it is evident that post-tensioning, by relieving the shores of load, improves the factor of safety. In this case, from an overload situation of 0.89 to a factor of safety of 1.0. There is however negligible difference between the undisturbed post-tensioned systems and either of the reshored systems for the particular parameters adopted.

Examining the factors of safety throughout the cycle indicates that the safety during the stripping and reshoring operation is enhanced for the post-tensioned systems. For example, level 2 at day 27 (strip) of the reshored systems, indicates an improved factor of safety from 1.14 for the reinforced system to 2.04 for the post-tensioned system as indicated in Table 2.

Table 1. Factor of safety for shoring scenarios

Shoring System	Slab Level	Day	Slab Age (days)	Slab Load Ratio	Factor of Safety
Undisturbed - Reinforced	3	42	21	2.37	0.89
Undisturbed - Post-tensioned	2	28	7	1.31	1.00
Reshored - Reinforced	3	28	14	1.85	1.01
Reinforced - Post-tensioned	3	28	7	1.31	1.00

Table 2. Factors of safety during stripping and reshoring

Shoring System	Slab Level	Day	Slab Age (days)	Slab Load Ratio	Factor of Safety
Reshored - Reinforced	2	27	13	1.51	1.14
Reshored - Post-tensioned	2	27	13	1.00	2.04

Improvements to the construction cycle time

Considering the undisturbed shoring procedures only, the factor of safety for the post-tensioned slab system is higher than that for the conventionally reinforced slab system (Table 1). Ignoring the fact that the undisturbed conventionally reinforced scenario is actually overloaded, to produce the same factor of safety in the undisturbed post-tensioned scenario, the pour cycle time could be shortened from 7 days to approximately 3 days; a saving of 4 days per slab on the construction time. Alternately, to raise the factor of safety for the conventionally reinforced scenario to that of the post-tensioned scenario, the pour cycle time for the conventionally reinforced scenario would need to increase to approximately 21 days. This would, however, be more efficiently accomplished by increasing the number of levels of shoring, thus avoiding increasing the pour cycle times unreasonably.

Reducing the formwork materials

Examining the shore loads for the reshored post-tensioned scenario (Figure 7) indicates that the formwork shores are fully relieved of their load when the slab is post-tensioned and are not reloaded until the next slab is poured. The scenario presented in Figure 8 details a situation in which the formwork is stripped and the slab reshored immediately following the post-tensioning of the slab. As the original formwork shores were not carrying load, there is no load redistribution as a result of this procedure.

This procedure allows for the slab formwork to be stripped at an earlier date than would normally be the case. In this particular scenario, the formwork from each slab is able to be removed 7 days earlier than the scenario presented in Figure 7 without altering the load distribution or factors of safety. This reduces the formwork material quantities from 2 sets of full formwork and 1 set of reshores to 1 set of full formwork and 2 sets of reshores. This is obviously subject to the development of suitable factors of safety.

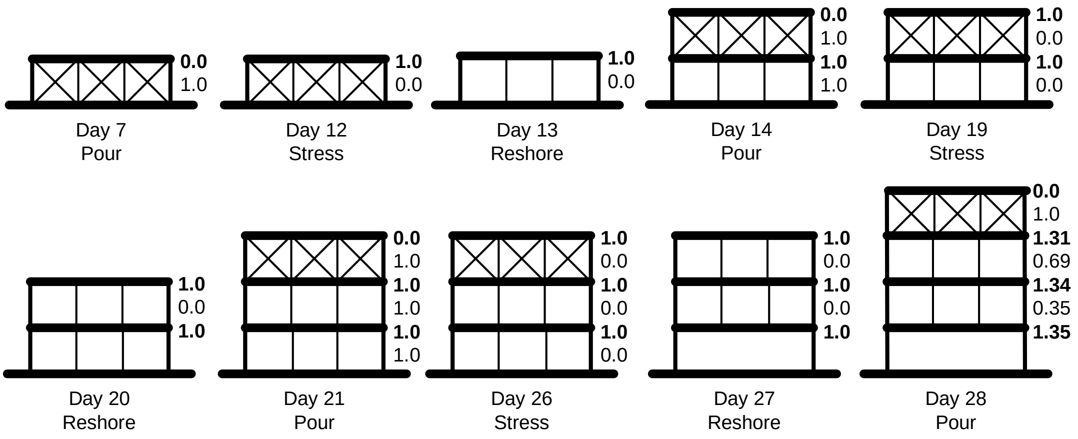


Figure 8. Early reshoring scenario

CONCLUSIONS

It was not the intention of this paper to present a fully detailed examination of the load distribution that occurs when multi-level formworking post-tensioned concrete slabs. The simple analysis method used however does serve to highlight some potential improvements to construction practice with post-tensioned slabs.

When using undisturbed supports on a multi-level project, it appears that the construction cycle can be shortened as there is an improvement in the factor of safety from the conventionally reinforced system to the post-tensioned system. This, however, is not the case with a reshored procedure as the factor of safety is approximately equal for both the conventionally reinforced and post-tensioned systems; a significant improvement in cycle times for a reshored system, therefore, appears unlikely.

Post-tensioning also has the potential to improve the factor of safety during the construction cycle. This is of particular importance for the stripping and reshoring operations during which construction personnel are required to work directly under the formwork structure and remove the shoring and formwork materials. The unloading of the shoring due to the stressing improves safety during this operation and allows the shoring and formwork to be removed more easily. Further, as the magnitude of the loads to be redistributed are lower for a post-tensioned structure, there is less danger of causing damage (excessive deflection, cracking, etc.) to slabs.

The unloading of the shores as the slab load is balanced by the post-tensioning allows for a significant level of reshoring to be undertaken without altering the load distribution in the interconnected formwork structure. As such, the number of fully reshored levels and full sets of formwork is able to be reduced allowing for a maximum of recycling, thereby, significantly reducing the cost of the formwork.

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